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13 ABSTRACT (Maximum 200 words)

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RECENT PROGRESS IN THE IMPLEMENTATION OF ACTIVE COMBUSTION CONTROL

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Abstract

Active combustion control has received increasing attention for the suppression of pressure oscillations and the extension of flammability limits in dump combustors and premixed combustors with flame-holders. In order to accelerate progress in this emerging area, a research program was initiated to improve the physical understanding of combustion dynamics, develop new actuators, and explore new control strategies. This paper describes progress made in the program. The role of shear-flow dynamics in combustion control through experiments and numerical large-eddy simulation has been clarified. New actuators to manipulate the shear layer and increase acoustic level by utilizing periodic chemical energy release have been demonstrated. New control strategies based on neural network, adaptive filter, and modern control synthesis procedures have been implemented.

I. Introduction

The suppression of combustion induced pressure oscillations and the extension of flammability limits are a major challenge in the design and development of high performance combustors. In the past, passive techniques have been used to control the combustion characteristics. In recent years, active combustion control has received increasing attention.

Passive control has historically involved modification to the fuel injection distribution pattern and changes to the combustor geometry. These modifications are often done during the test phase of a development program, and are based on the engineer's prior experience rather than a detailed physical understanding of the complex combustion process. More recently, passive control of the combustion characteristics has been achieved by utilizing an understanding of the shear-flow dynamics behind a bluff-body flameholders of a premixed combustor and at the downstream facing step into a dump combustor.[1] For example, in the dump combustor, nonstandard inlet duct cross-sections were used to control the generation and breakdown of large-scale structures, which play a critical role in driving pressure oscillations and determining the flammability limits.

In active control, actuators are used to modify the pressure field in the system and modulate the air or fuel supply to suppress combustion oscillations. Typically, a feedback control loop is used to drive an actuator using the processed output from a sensor which monitors the flame characteristics or pressure oscillations. Different active control schemes have been tested and resulted in suppression of pressure oscillations and extension of flammability limits in laboratory combustors with heat release rates up to 250 kW, in operation at ambient pressure and with gaseous fuels. An extensive review of recent active control work has been recently done by McManus.[2]

In 1987, the US Office of Naval Research (ONR) initiated a research program to explore active combustion control in dump combustors and premixed combustors with flameholders (Figure 1). Specific goals included extending the demonstration of control with gaseous fuels to liquid fuels; control of a combustor at significant energy release rates (greater than 1 MW); and explore the utility of control at higher combustor pressure. The overall approach to obtain control authority at these more practical operational conditions has been to apply the physical understanding of the shear-layer and combustion dynamics to guide the development of new actuators and appropriate control theory. The active manipulation of the reacting shear layer downstream of the dump or behind bluff bodies was examined as a possible candidate for control of the combustion dynamics. Experiments in flames and laboratory combustors using advanced diagnostics, combined with numerical large-eddy simulations (LES) are being used. In the combustor experiments, novel actuators are being explored to actively control the shear-flow development and allow operation at elevated pressures. For feedback control, standard and advanced control techniques are being explored, including modern control

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synthesis procedures, adaptive filters, and neural networks. In the ONR program, standard sensors were used, including high-frequency response pressure transducers, microphones, and CH emission sensors.

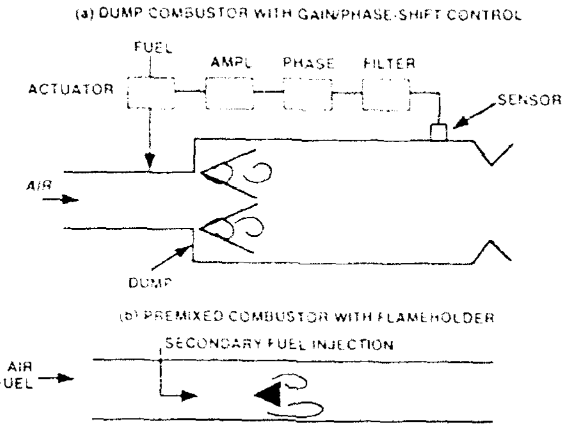

FIGURE 1. Dump Combustor and Premixed Combustor with Flameholder for Active Combustion Control Experiments.

This paper presents the progress to date made by several investigators in the ONR program. Participants in the Active Control Program include Barron Associates, Inc., Stanardsville, Virginia; California Institute of Technology, Pasadena, California; General Electric Corporate Research and Development, Schenectady, New York; Imperial College of Science, Technology and Medicine, London, England; Naval Air Warfare Center Weapons Division, China Lake, California; Naval Command, Control and Ocean Surveillance Center, San Diego, California; Quest Integrated, Inc., Kent, Washington; Stanford University, Stanford, California. In the following sections of the paper, progress in the following areas is reviewed: (1) physical understanding of the combustion dynamics, (2) development and testing of new types of actuators, (3) implementation of novel *feedback control techniques*, and (4) demonstration of active combustion control in combustors up to 1 MW.

II. Physical Understanding of Combustion Dynamics

Combustion characteristics are closely related to detailed fluid dynamic processes. In dump combustors, for example, combustion features such as flammability limits and combustion stability depend on the evolution of large-scale structures and their breakdown into fine-scale mixing which occurs in the shear layer developing downstream of the dump.[3,4] By changing the initial conditions of the shear layer using non-circular geometries, the shear-flow dynamics were passively controlled for extended flammability limits and improved combustion stability as visualized in flames using advanced diagnostics.[1] In a similar approach, advanced diagnostics were also applied to *study the effect of active control on the shear-flow* and combustion dynamics. Figure 2 shows both the changing shear-flow dynamics and pressure signal in a ducted flame during the transition from uncontrolled to closed-loop control operation.[5] During the uncontrolled (unstable) state, high amplitude pressure oscillations in the duct are associated with the development of large-scale vortices at the burner lip as visualized by a CH emission imaging system. To control the flame stability, the acoustic signal was picked up by a microphone, time-delayed, filtered, amplified, and fed back to activate an acoustic driver which modulated the air/fuel mixture. As seen in Figure 2, the suppression of the oscillations is clearly associated with preventing the development of coherent structures.[1,3]

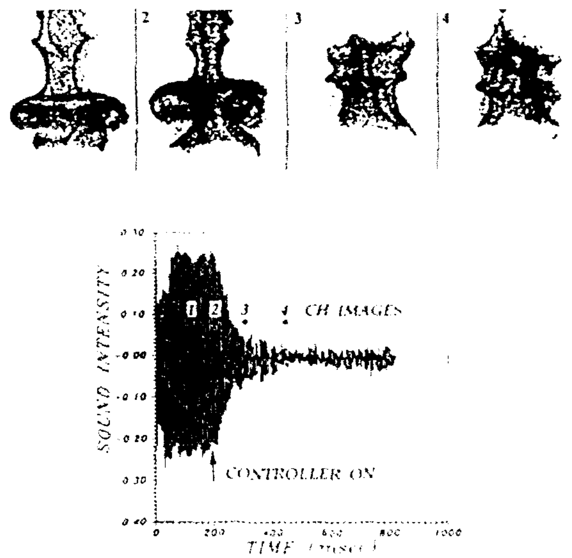

FIGURE 2. Flame Dynamics and Pressure Signal During Transition for Uncontrolled to Controlled Operation using Gain/Time-Delay Controller.

Open-loop control in the ducted flame was initially used to enhance flame stability and extended flammability limits, by forcing the flame at higher harmonics of the pressure oscillations to disrupt development of large-scale structures and generate small-scale vortices. Based on this shear layer forcing near the Kelvin-Helmholtz instability frequency, the closed-loop amplitude modulation controller was developed to control initiation of reaction in the flame.[6]

The critical role of *shear-flow* dynamics identified in the flame experiments was used to guide active-control studies in a 12.5-cm diameter dump combustor with a nominal heat release rate of 3 MW. In this combustor, the critical role of large-scale structures in driving pressure oscillations have been previously identified using planar laser diagnostics.[3] A special combustor design was utilized in the tests. [illegible] injection was done through an orifice plate at the dump (Fig 3).[7] With this design, the shear layer, which separates from the orifice, is thinner than in the standard dump combustor and is therefore more susceptible to excitation (corresponding to higher amplification rates). Also, the fuel is injected directly into the shear layer such that fuel modulations are more likely to affect the combustion process. In simulated combustion tests, the effectiveness of manipulating the shear layer with "fuel" modulations was demonstrated.[8] In these nonreacting experiments, acoustic forcing of the inlet-duct flow was used to simulate combustion oscillations; as a result, coherent vortices were shed from the dump as indicated by a peak in the velocity spectrum and flow visualization using Mie scattering. An acoustic actuator was then used to modulate "fuel" jets at the phase-shifted instability frequency. With proper phase adjustment, the active control was able to disrupt periodic vortex shedding at the dump, indicated by elimination of the velocity peak in the spectrum.

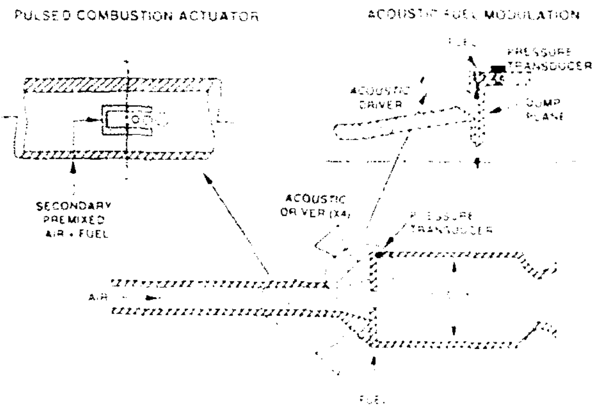

FIGURE 3. Schematic of Dump Combustor with Pulsed-Combustion Actuator and Acoustic Fuel Modulation.

A large-eddy numerical simulation (LES) technique was used to provide insight into the combustion dynamics. An LES simulation was used which contains the essential physics of combustion instability, including unsteady, turbulent, compressible reacting flows and acoustic, vorticity, and entropy waves.[9,10] The combustion was simulated using a thin-flame model that explicitly determines the turbulent flame speed as a function of the laminar flame speed and subgrid turbulent kinetic energy. Figure 4a shows an example of flame and vorticity [illegible] simulation of an unsteady dump combustor in operation. Figure 4b shows a simulation [illegible] pulsed secondary fuel [illegible]

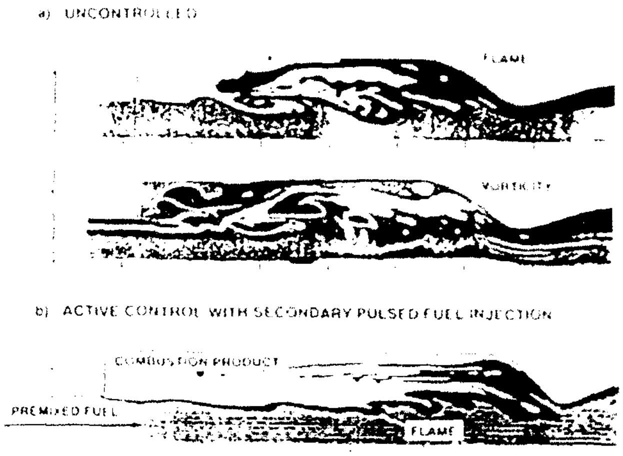

FIGURE 4. Large-Eddy Simulation of Uncontrolled and Actively Controlled Combustion Dynamics using Pulsed Secondary Fuel Injection.

Additional insight into the effectiveness of active control on shear-flow dynamics was gained from experiments with a premixed, two-dimensional combustor.[12] Results of these experiments will be discussed in the following section related to novel actuators.

The physical understanding of the combustion dynamics provided by the previously described work was critical for placement and choice of actuators to optimize control authority. Actuators explored in the present program, will be described in the following section.

III. Actuators

Several different types of actuators were used in earlier active control experiments. These included (1) loudspeakers to modify the pressure field of the system[13] or to obtain gaseous fuel flow modulation,[14] (2) pulsed gas jets aligned across a rearward facing step,[15] (3) adjustable inlets for time-variant change of the inlet area of a combustor,[16] and (4) solenoid-type fuel injectors for controlled unsteady addition of secondary fuel into the main combustion zone.[17]

Several new types of actuators were explored in the ONR program. Their design and performance are summarized in the following.

In a laboratory-scale premixed, two-dimensional dump combustor the combination of vortex generators and spanwise vorticity generators was explored (Figure 5).[12] Streamwise vorticity was introduced into the inlet flow with two jets, skewed at 45 degrees towards the side walls. These jets with controllable momentum flux produced one dominant pair of counter-rotating vortices, which increased the volumetric [illegible] [illegible] combustion instability [illegible] addition of spanwise forcing resulted in reduced pressure oscillations by producing a periodic cross-stream flow perturbation to the inlet boundary layer through a slot which spanned the entire inlet width. A loudspeaker was utilized as a forcing element. The control of energy release and combustion instability was a function of jet momentum, speaker voltage and frequency, which makes this technique an effective actuator for active control as described later. For this combined control technique, the effect of forcing on the flame structures may be seen from Schlieren images in Figure 6. With spanwise and streamwise forcing (Figure 6d), the flame is highly three dimensional and reveals the presence of small-scale vortices. In the experiments shown in Figure 6, the vortex generating jets were replaced by delta-wing vortex generators.

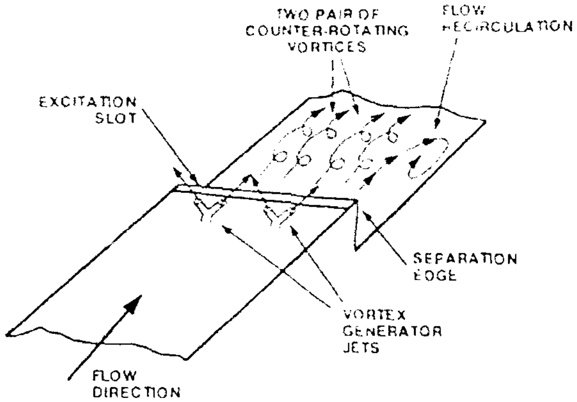

FIGURE 5. Combination of Streamwise and Spanwise Vortex Generators in Premixed, Two-Dimensional Dump Combustor.

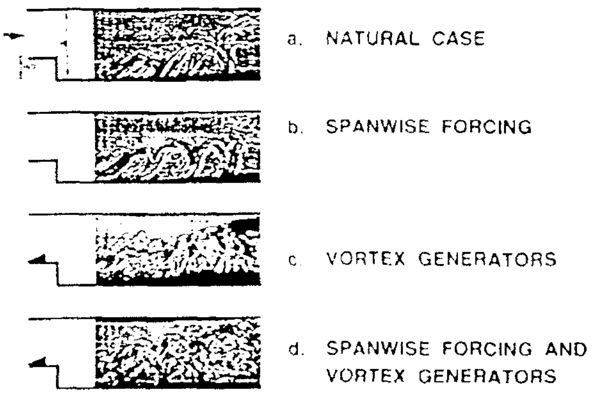

FIGURE 6. Effect of Spanwise and Streamwise Forcing on Flame Structure using Schlieren Photography.

For time-variant fuel injection, different techniques were explored. For gaseous fuels, a needle valve driven by a vibrator was used.[18] Tests were made using arrangements in which secondary fuel was injected radially into the premixed combustor upstream of the bluff-body flameholder and with the secondary fuel added to a secondary airstream which was injected either radially or axially into the duct. Injection of the oscillated fuel alone into the duct sometimes led to early blowoff. The oscillation of the secondary fuel was proportional to the amplitude of the needle-valve oscillation, but was subject to damping by a factor of order 5 due to the effects of diffusion and convection in the feed lines. Also phase and amplitude of fuel oscillations were difficult to quantify for closed-loop active control, in particular for frequencies above 200 Hz. Nevertheless, successful suppression of combustion oscillations was obtained as discussed later. Gaseous fuel modulation by loudspeaker was also explored in the 12.5-cm dump combustor.[7] Acoustic modulations were superimposed on the fuel stream through four tubes which were connected to 75 W acoustic drivers (Figure 3).

For liquid fuels, a Moog servo-valve was modified to obtain high-speed fuel-injector actuation up to 250 Hz.[19] To obtain the high frequency response, a process controller with dynamic signal analyzer was used for closed-loop servo-valve control (Figure 7). The valve was tested in a premixed combustor with the flame stabilized behind a standard V-gutter flameholder and a system with improved flameholding using a swirler. With the swirler, the reaction zone was shortened by a factor of about 4. For the V-gutter flameholder, an unsatisfactory correlation between the fuel oscillation pressure P_{FUEL} downstream of the valve and the chamber pressure P_{CHAM} downstream of the flameholder was obtained. With the swirl flameholder, the correlation was significantly improved (Figure 8).

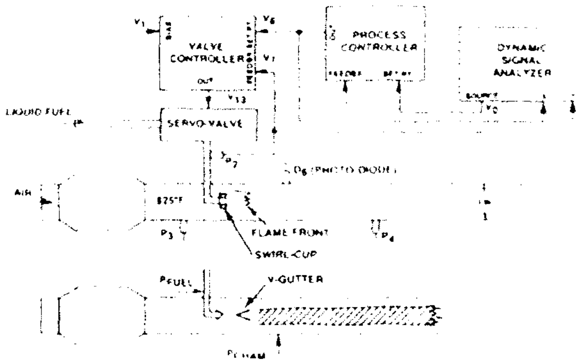

FIGURE 7 Relative Flame Zone Length for Swirl Cup and V-Gutter Flameholder using Closed-Loop Control for High Frequency Fuel Modulation

In another attempt to achieve actuation at elevated combustor pressure, a disk was used as part of the combustor wall and oscillated by a vibrator.[20] However the acoustic power input of the oscillating disk diagram decreased to an insufficient level for a frequency greater than 100 Hz.

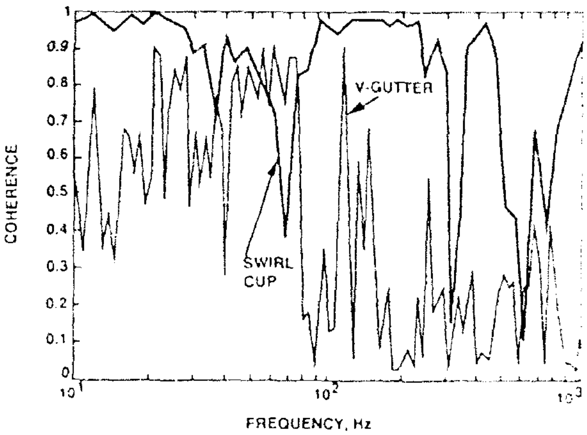

FIGURE 8. Coherence Between Fuel Pressure Modulation and Chamber Pressure Oscillation for Combustor Configurations Shown in Figure 7.

The most promising actuator was developed using periodic chemical heat release to increase acoustic power level while maintaining amplitude and phase control and allowing operation at elevated pressures. The principle of operation is based on convected flame kernels in a duct of premixed fuel and air which produce pressure oscillations due to their energy release (Figure 3).[21] To avoid merging of the kernels, the flame speed is smaller than the gas velocity that is convecting the kernels. The actuator with 70 W energy input for the spark ignition was tested in a frequency range of 50-1000 Hz at up to 240 kPa operating pressure using gaseous ethylene fuel.

Enhanced physical understanding of the combustion dynamics, combined with novel actuators provide the potential to obtain active control at higher energy levels. In addition, attempts are being made to find new stabilizing controllers. Progress is described in the following section.

IV. Controller

Previous work in active control has utilized phase-shift/time-delay type controllers (Figure 1). The utilization of active control concepts in practical combustion systems require feedback control strategies which are adaptive and capable of multi-frequency instability control. Several novel approaches are being examined in the ONR program. In a [illegible] analytical approach in simulating the unsteady [illegible] field related to combustion instabilities was studied. This work, which ultimately supports the design of controllers, will be described first. Subsequently, [illegible]

Approximate Analysis

So-called approximate analysis is used as the theoretical framework to explicitly represent all gas dynamic processes including some nonlinear terms while accommodating other physical processes by modeling.[22] The analysis is considered general because when a specific case of combustion instabilities is considered unsteady heat addition needs to be modeled in some fashion. In formulating the analysis, fluctuating value equations are obtained for the flow variables from the governing equations of fluid motion. Subsequently, a form of Galerkin's method is applied in which the acoustic modes of the combustion chamber are used as the basis functions. The governing partial differential equations are finally reduced to a set of second-order ordinary differential equations written for time-dependent amplitude of the corresponding acoustic mode. The approximate analysis was applied to a Rijke tube by incorporating a model for unsteady heat addition with two parameters. Results and comparison to experimental data are discussed later.

Controllers Using Loop Shaping Techniques

To extend performance of simple phase-shift controllers, a classical approach using a frequency domain compensator was undertaken. This digital controller, which was designed for a ducted premixed flame, consisted of an 8th order Butterworth filter, a second-order notch filter, a first-order lead compensator, and a gain module. The design procedure is illustrated in Ref. 23, and its improved performance and stability robustness was experimentally demonstrated.

The successful implementation of active instability suppression in complex combustor geometries will require a multi-frequency controller with the ability to suppress closely spaced resonance modes. Controllers for this purpose have been designed and applied to the Rijke tube[24] using loop shaping H_∞ techniques. By utilizing a simplified linear model for the acoustic dynamics and doing system identification measurements, a transfer function was approximated, which was in satisfactory agreement with the measured transfer function (Figure 9). The loop shaping controller design procedure, described in Reference 25, was then used to design a controller for the Rijke tube experiments.

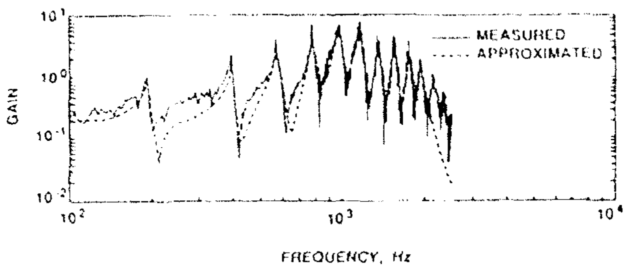

FIGURE 9 Measured Transfer Function and Analytical Approximation.

Knowledge Based Control

Knowledge based control was applied to a ducted premixed flame as well.[18] In a knowledge based controller, the signal from a pressure transducer in the combustor was fed back with constant gain through a bandpass filter to a phase shifting device to drive an actuator to obtain oscillation suppression. The phase shifter monitored the filtered feedback signal to give a synthesized sinusoid locked to the feedback with a switch-selectable phase shift at 256 equal intervals between 0 and 360°. The software-controlled output voltage (input voltage to the vibrator) could be incremented in the ratio $2^{n/4}$, where n was any integer between 0 and 63. The characteristics of the actuator determined that their peak-to-peak displacements were proportional to the input voltage.

The performance of the knowledge based control with variable input to the actuator is compared later to a controller with constant input.

Adaptive Filter

An adaptive filter controller was also used on a ducted premixed flame. The adaptive controller was a modified adaptive filter, which utilized a digital implementation of the Wiener-Hopf least-mean-squares algorithm for adaptation.[26] The filter was modified to allow differencing of the performance and input signal externally. The bandpass filtered pressure transducer signal was amplified to produce the detector and error signals with voltage gains of around 10 (20 dB) over the filtered signal.

Dynamic Polynomial Neural Networks

The utility of neural networks for quasistatic problems such as pattern recognition is well established. Their suitability for the dynamic problems of system identification and control is less well known. In the present program, work has been supported to develop [illegible] network architectures which are suited to the dynamic environment. They have concentrated on [illegible] whose elements have internal time delays [illegible]. Additionally, network synthesis methods have been developed which employ information theory to constrain the number of network nodes to the minimum required for accurate system identification. A discussion of this concept of polynomial neural networks (PNN) is given in Ref. 27.

The implementation of a controller based on PNN is being explored in a premixed combustor with combined *streamwise and spanwise forcing* (Figure 5) and in a dump combustor with acoustic fuel modulation using the time-delayed pressure oscillation frequency (Figure 3).

For the premixed combustor,[28] control inputs are jet-to-cross flow ratio, R, for the streamwise forcing and speaker voltage, A, and frequency, f, for spanwise forcing. These inputs are controlled for varying equivalence ratio, ϕ, and inlet velocity, U_o, to minimize RMS pressure fluctuation level, P, and maximize volumetric energy release rate, E, as indicated by CH emission. For these interrelated combustor parameters, a response surface was generated from static actuator inputs for varying combustor conditions. Subsequently a cost function was defined representative of the desired operating characteristics. Optimum control is obtained by minimizing the cost function

$$J = aP^2 - bE^2$$

where P and E are the respective response surfaces represented by the neural net:

$$P = f(R, A, f, \phi, U_o)$$

$$E = g(R, A, f, \phi, U_o)$$

The weighing coefficients a and b allow shifting the emphasis between minimizing P and maximizing E. Figure 10 shows the effect of varying a and constant b on the cost function based on actual combustor data and neural net predictions. Work is in progress to complete training of the neural net and allow on-line re-minimization of the cost function by active search in control parameter space.

For the dump combustor (Figure 11),[29] a PNN controller was used to determine the optimum time-delay, TD* between pressure oscillations and fuel modulation to minimize RMS pressure fluctuations, IFPAMP and optimize heat release rate (CH emission) at the combustion chamber center, EAVR2. The cost function for this controller was defined as follows:

$$J = IFPAMP + 1/EAVR2$$

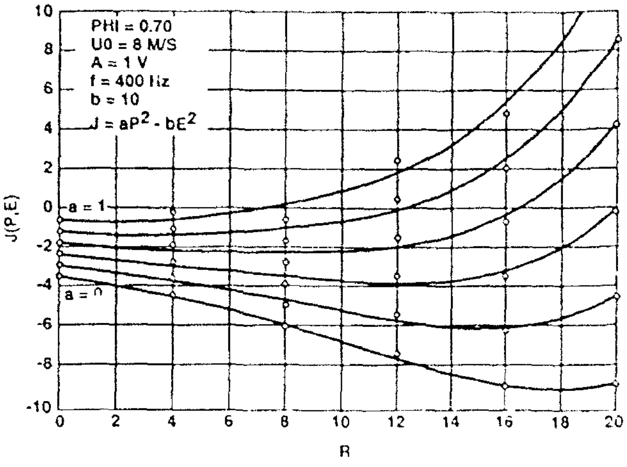

FIGURE 10. Effect of Pressure Response Surface Weighting Factor on Cost Function Determined from Static Experiments and Polynomial Neural Network.

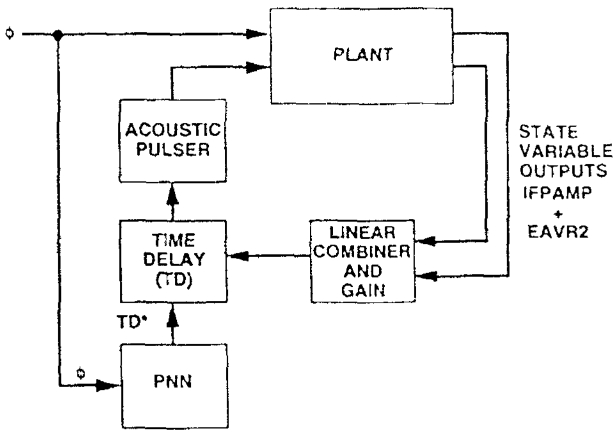

FIGURE 11. Feed Forward Neural Net Controller to Optimize Time Delay for Varying Equivalence Ratio.

Based on experiments in which IFPAMP and EAVR2 was systematically determined as a function of TD* and ϕ, the cost (or performance) function J in Figure 12 was calculated based on PNN. Depending on ϕ, this surface determines TD to minimize J (or maximize EAVR2 and minimize IFPAMP). At the present time, the PNN controller is being explored in off-line operation. For varying equivalence ratio, TD* was calculated with the performance function and manually adjusted in the control loop. Results are discussed in Section V

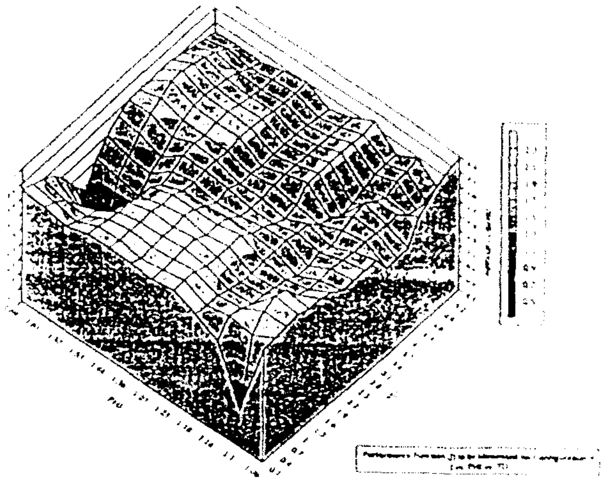

FIGURE 12. Performance (Cost) Function J to be Minimized for Optimum Performance as Function of Equivalence Ratio.

V. Active Control Experiments

Closed-loop active control experiments were conducted in four combustion devices in the ONR research program. The goal was to explore the new approaches based on improved physical understanding, new actuators, and improved control theory: (1) Rijke tube with loudspeaker (multi-mode controller, evaluation of plant model), (2) 1-kW premixed combustor with loudspeaker (improved gain/ phase-shift controller with stabilizing compensator), (3) 50 and 100 kW premixed combustors, with loudspeakers and secondary fuel injection (control with variable input amplitude and adaptive filter), and (4) 1 MW dump combustor with fuel modulation (loudspeaker) and pulsed-combustion actuator (gain/time-delay controller, neural net). Experimental arrangements (1) to (3) were used to suppress pressure oscillations. Arrangement (4) was used to extend flammability limits in addition to oscillation control.

Rijke Tube

The acoustic mode predictions of the approximate analysis for the Rijke tube were compared to an experiment in which a thin electrically heated wire grid was used as the energy source. Comparison of the pressure spectra as shown in Figure 13 reveals a good agreement of the instability frequencies, but the agreement between the relative amplitudes of each mode is still poor. The Rijke tube is one of the simplest examples of thermally driven oscillations, it is evident that much work is still needed before an accurate theoretical prediction of combustion instability in a complex device.

In the same device, the H_∞ controller designed with loop shaping [illegible] was able to control multiple unstable modes.[24] As shown in Figure 14, suppression of multi-frequency oscillations was obtained in closed loop operation.

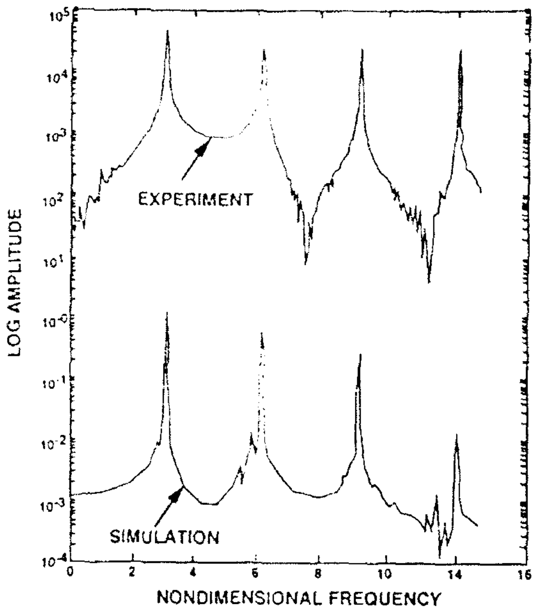

FIGURE 13. Experimental and Simulated Acoustic Modes in Rijke Tube.

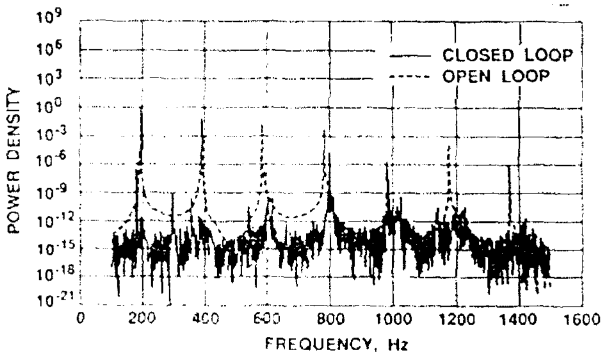

FIGURE 14. Closed and Open Loop Spectrum in Rijke Tube Using Controller With Loop Shaping H_∞ Techniques.

Premixed Combustor (1 kW)

Experiments were conducted in a premixed *methane-air combustor.*[30] The flameholder consisted of a perforated plate with 80 holes and was located midway inside the combustor. The 1-kW combustor exhibited large self-sustained oscillations, predominantly at 380 Hz (three-quarter wave) and 760 Hz (second harmonic). A loudspeaker was mounted at the head end of the combustor. A simple gain/phase-shift controller suppressed the oscillations over only a limited range of inlet flow conditions, in terms of total flow rate and equivalence ratio. Even in the effective range of suppression, the controller had a limited allowable gain and phase-shift margin, probably due a multiplicity of closely spaced instability modes. An improved controller with lead compensator and notch filter was designed using frequency-response data and standard design laws, resulting in a more robust controller with a wider gain and phase margin and improved range of effectiveness. An attenuation of 33 dB was achieved at the 1 kW energy level for the pressure oscillations with uncontrolled $\Delta P_{RMS} = 0.2$ kPa.

Premixed Combustor (50 and 100 kW)

Several actuators were evaluated in this pipe combustor *with premixed propane/air* stabilized behind a bluff body. Only the experiments with secondary fuel injection, modulated by a needle valve, will be discussed here.[18] Two combustor diameters of 40 mm and 80 mm, with heat release rates of about 50 and 100 kW, were used.

A simple gain/phase-shift controller providing a constant input amplitude to the needle valve resulted in periodic loss of lock between actuator input and feedback, and limited attenuation of the 120 Hz-quarter wave pressure oscillations to 10 dB (a factor of 3). A controller with variable input amplitude (knowledge-based controller) averted loss of lock between actuator input and feedback and improved attenuation of pressure oscillations by 5 dB to 15 dB (the latter being a factor of 5) (Figure 15).

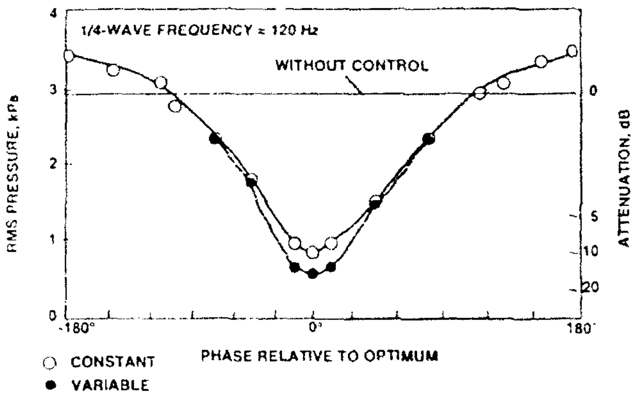

FIGURE 15. Suppression of Pressure Oscillations with Constant and Variable Input Amplitude to *Secondary Fuel Actuator.*

The effectiveness of control in this type of combustor was limited by the heat release rate. Attenuation of oscillations by up to 15 dB was possible for heat release rates up to 100 kW. Attenuation decreased with heat release rate to values below 5 dB for heat release greater than 160 kW in the 80-mm pipe (Figure 16).

Preliminary tests with the adaptive filter showed that this control was more effective than knowledge-based control due to effective tracking of the frequency. A reduction of 20 dB (a factor of 10) of a 120 Hz pressure oscillation was obtained.[31]

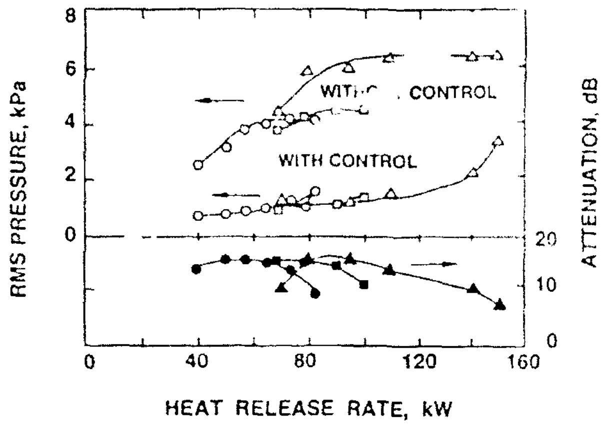

FIGURE 16. Influence of Combustor Heat Release on Attenuation.

Dump Combustor

Active combustion control was tested in the 12.5-cm diameter combustor for heat release rates up to 1 MW and combustor pressure up to 180 kPa. Three test conditions will be reviewed. (1) For 250 and 500 kW operation at nearly ambient pressure, acoustic drivers modulated the ethylene flow rate at the combustion instability frequency with varying phase shift relative to the instability. (2) For 1 MW operation at 180 kPa, the pulsed-combustion actuator using 2% of the total mass flow was located in the inlet duct and operated with a simple gain/phase-shift controller. (3) Preliminary tests were made to evaluate the neural net controller at 33 kW and ambient pressure operation with fuel modulation using a loudspeaker.

For 250 kW and 500 kW operation at ambient pressure, peak amplitude and RMS of the 300 Hz instability was suppressed at 40 degrees phase angle. The maximum suppression was 47% of the peak amplitude (5 dB attenuation). The controlled fuel oscillations also extended the lean flammability limit.[7] For similar operational conditions, a dual-loop feedback control system was employed to suppress pressure oscillations during a bi-modal combustion instability. The sensor signal was fed back into the acoustic drivers via two separate channels, with different time delays (transfer functions). When the transfer functions for both channels were optimized for the suppression of its corresponding frequency, the combined dual-mode system was effective in suppressing the bi-modal frequency and delayed onset of high level instability oscillations at the lean flammability limit. The flame blow-out was reduced from an equivalence ratio of 0.72 to 0.54 (Figure 17).[32]

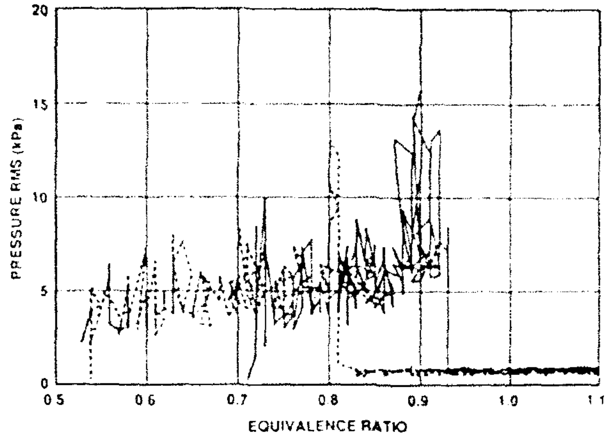

FIGURE 17. Extension of Lean Flammability Limit by Dual-Mode Active Control Using Gain/Time-Delay Controller and Acoustic Fuel Modulation, 500 kW Dump Combustor.

For 1 MW operation at 180 kPa, the peak values of a 140 Hz instability was reduced by 28% at a phase angle of about 30 degrees (Figure 18). The natural RMS pressure fluctuations was 25.4 kPa or 182 dB. Higher attenuation is expected when the pulsed combustion actuator (flame kernel) concept will be used for direct shear-layer excitation.

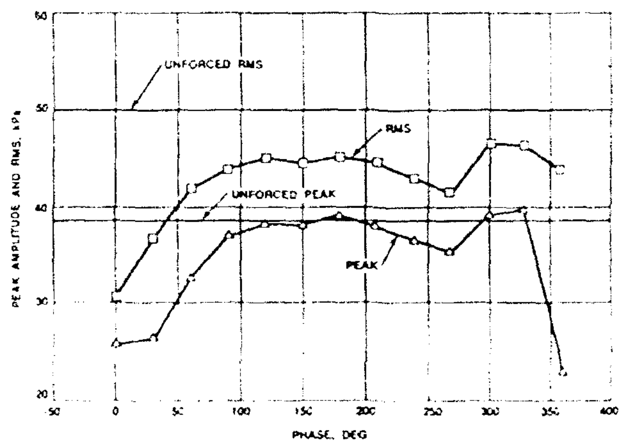

FIGURE 18. Suppression of Peak Amplitude Using Gain/Phase-Shift Controller and Pulsed-Combustion Actuator, 1 MW Dump Combustor at 180 kPa Chamber Pressure.

For 33 kW operation at ambient chamber pressure, peak pressure was suppressed by up to 15 dB and CH emission increased over the entire equivalence-ratio range when the time delay for each ϕ was calculated by the PNN performance surface (Figure 19). Experiments are continuing to test the PNN controller in closed loop operation, as shown in Figure 11.

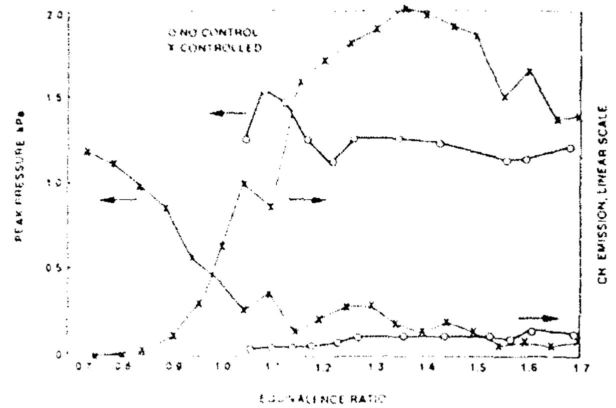

FIGURE 19. Peak Pressure and CH Emission Control with Acoustic Fuel Modulation using Neural Net to Determine Time-Delay for Varying Equivalence Ratio, 33 kW Dump Combustor at Ambient Chamber Pressure.

VI. Conclusions

It is clear that active control is a viable approach to suppress combustion instabilities and extend flammability limits of a variety of combustion systems. A detailed physical understanding of the combustion/acoustic processes gained from experiments and simulation was an important tool in the successful implementation of control. Several control methodologies have demonstrated potential.

Active control has been extended to test conditions which approach operational energy and pressure levels. These tests pointed towards the need for a more effective actuator that could produce high acoustic power at elevated pressures. The development of the flame kernel actuator based on periodic chemical heat release may be the most important advance to date. Until this new actuator, the trend in active combustion control experiments was towards decreasing performance with increasing energy and pressure levels.

A second area of continuing investigation should be the combined use of active and passive control methods. Experiments to date in laboratory scale combustion systems suggest that the two approaches can be used effectively in combination more satisfactorily than either one alone. It is plausible that the same will be true in other systems and processes, but the question has not yet been explored in detail.

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